IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant:	Viatcheslav V. Osipov and Alexandre M. Bratkovski		
Assignee:	Hewlett-Packard Development Company, L.P.		
Title:	SPIN INJECTION DEVICES		
Serial No.:	10/631,999	Filing Date:	July 30, 2003
Examiner:	Fernando L. Toledo	Group Art Unit:	2823
Docket No.:	200300477-1		

DECLARATION OF INVENTOR PURSUANT TO 37 C.F.R. § 1.132 TRAVERSING REJECTIONS

I, Alexandre M. Bratkovski, hereby declare that I have authored or co-authored 11 published papers regarding spintronics and am very familiar with spintronic devices;

I have reviewed the section entitled Spintronic Devices in Sankar Das Sarma, "Spintronics," American Scientist Vol. 89, pp 516-523 (2001); and

I believe that the phrase "gate current" in the third column of page 518 of Sarma, "Spintronics," American Scientist Vol. 89, pp 516-523 (2001) is a typographical error because the Datta-Das spin transistor is known to use a gate voltage (not current) to control spin precession.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Title 18, United States Code,

THE PATENT LAW OFFICES
OF DAVID MILLERS
6560 ASHFIELD COURT
SAN JOSE, CA 95120

PH: (408) 927-6700
FX: (408) 927-6701

§ 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

AMBratkovski 2/28/06

Alexandre M. Bratkovski Date

THE PATENT LAW OFFICES
OF DAVID MILLERS
6560 ASHFIELD COURT
SAN JOSE, CA 95120

PH: (408) 927-6700
FX: (408) 927-6701

REVIEWS OF MODERN PHYSICS, VOLUME 76, APRIL 2004

Spintronics: Fundamentals and applications

Igor Žutić*

Condensed Matter Theory Center, Department of Physics, University of Maryland at College Park, College Park, Maryland 20742-4111, USA

Jaroslav Fabian†

Institute for Theoretical Physics, Karl-Franzens University, Universitätsplatz 5, 8010 Graz, Austria

S. Das Sarma

Condensed Matter Theory Center, Department of Physics, University of Maryland at College Park, College Park, Maryland 20742-4111, USA

(Published 23 April 2004)

Spintronics, or spin electronics, involves the study of active control and manipulation of spin degrees of freedom in solid-state systems. This article reviews the current status of this subject, including both recent advances and well-established results. The primary focus is on the basic physical principles underlying the generation of carrier spin polarization, spin dynamics, and spin-polarized transport in semiconductors and metals. Spin transport differs from charge transport in that spin is a nonconserved quantity in solids due to spin-orbit and hyperfine coupling. The authors discuss in detail spin decoherence mechanisms in metals and semiconductors. Various theories of spin injection and spin-polarized transport are applied to hybrid structures relevant to spin-based devices and fundamental studies of materials properties. Experimental work is reviewed with the emphasis on projected applications, in which external electric and magnetic fields and illumination by light will be used to control spin and charge dynamics to create new functionalities not feasible or ineffective with conventional electronics.

CONTENTS

I. INTRODUCTION

A. Overview

Spintronics is a multidisciplinary field whose central theme is the active manipulation of spin degrees of free-

*Present address: Center for Computational Materials Science, Naval Research Laboratory, Washington, D.C. 20735, USA. Electronic address: igorz@physics.umd.edu
†Electronic address: jaroslav.fabian@uni-graz.at

0034-6861/2004/76(2)/323(88)/$40.00

dom in solid-state systems.[1] In this article the term spin stands for either the spin of a single electron **s**, which can be detected by its magnetic moment $-g\mu_B\mathbf{s}$ (μ_B is the Bohr magneton and g is the electron g factor, in a solid generally different from the free-electron value of $g_0=2.0023$), or the average spin of an ensemble of electrons, manifested by magnetization. The control of spin is then a control of either the population and the phase of the spin of an ensemble of particles, or a coherent spin manipulation of a single or a few-spin system. The goal of spintronics is to understand the interaction between the particle spin and its solid-state environments and to make useful devices using the acquired knowledge. Fundamental studies of spintronics include investigations of spin transport in electronic materials, as well as of spin dynamics and spin relaxation. Typical questions that are posed are (a) what is an effective way to polarize a spin system? (b) how long is the system able to remember its spin orientation? and (c) how can spin be detected?

Generation of spin polarization usually means creating a nonequilibrium spin population. This can be achieved in several ways. While traditionally spin has been oriented using optical techniques in which circularly polarized photons transfer their angular momenta to electrons, for device applications electrical spin injection is more desirable. In electrical spin injection a magnetic electrode is connected to the sample. When the current drives spin-polarized electrons from the electrode to the sample, nonequilibrium spin accumulates there. The rate of spin accumulation depends on spin relaxation, the process of bringing the accumulated spin population back to equilibrium. There are several mechanisms of spin relaxation, most involving spin-orbit coupling to provide the spin-dependent potential, in combination with momentum scattering to provide a randomizing force. Typical time scales for spin relaxation in electronic systems are measured in nanoseconds, while the range is from picoseconds to microseconds. Spin detection, also part of a generic spintronic scheme, typically relies on sensing the changes in the signals caused by the presence of nonequilibrium spin in the system. The common goal in many spintronic devices is to maximize the spin detection sensitivity to the point that it detects not the spin itself, but changes in the spin states.

Let us illustrate the generic spintronic scheme on a prototypical device, the Datta-Das *spin field-effect transistor* (SFET; Datta and Das, 1990), depicted in Fig. 1. The scheme shows the structure of the usual FET, with a drain, a source, a narrow channel, and a gate for controlling the current. The gate either allows the current to flow (ON) or does not (OFF). The spin transistor is similar in that the result is also a control of the charge current through the narrow channel. The difference, however, is in the physical realization of the current control. In the Datta-Das SFET the source and the drain are ferromagnets acting as the injector and detector of the electron spin. The drain injects electrons with spins parallel to the transport direction. The electrons are transported ballistically through the channel. When they arrive at the drain, their spin is detected. In a simplified picture, the electron can enter the drain (ON) if its spin points in the same direction as the spin of the drain. Otherwise it is scattered away (OFF). The role of the gate is to generate an effective magnetic field (in the direction of **Ω** in Fig. 1), arising from the spin-orbit coupling in the substrate material, from the confinement geometry of the transport channel, and the electrostatic potential of the gate. This effective magnetic field causes the electron spins to precess. By modifying the voltage, one can cause the precession to lead to either parallel or antiparallel (or anything between) electron spin at the drain, effectively controlling the current.

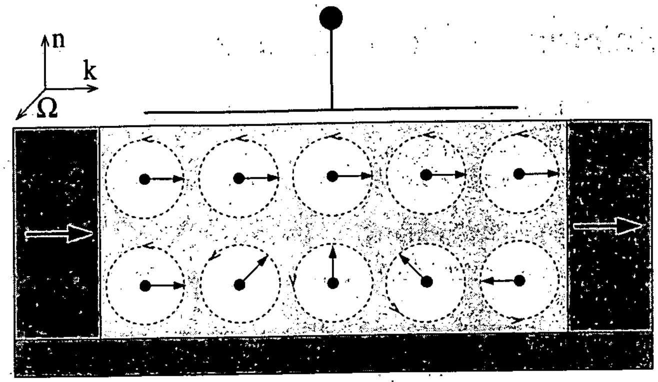

FIG. 1. (Color in online edition) Scheme of the Datta-Das spin field-effect transistor (SFET). The source (spin injector) and the drain (spin detector) are ferromagnetic metals or semiconductors, with parallel magnetic moments. The injected spin-polarized electrons with wave vector **k** move ballistically along a quasi-one-dimensional channel formed by, for example, an InGaAs/InAlAs heterojunction in a plane normal to **n**. Electron spins precess about the precession vector **Ω**, which arises from spin-orbit coupling and which is defined by the structure and the materials properties of the channel. The magnitude of **Ω** is tunable by the gate voltage V_G at the top of the channel. The current is large if the electron spin at the drain points in the initial direction (top row)—for example, if the precession period is much larger than the time of flight—and small if the direction is reversed (bottom).

Even though the name *spintronics* is rather novel,[2] contemporary research in spintronics relies closely on a long tradition of results obtained in diverse areas of physics (for example, magnetism, semiconductor physics, superconductivity, optics, and mesoscopic physics) and establishes new connections between its different subfields (Rashba, 2002c; Žutić, 2002a). We review here both well-established results and the physical principles

[1]While there are proposals for spintronic devices based on deoxyribonucleic acid (DNA) molecules (Zwolak and Di Ventra, 2002), the whole device, which includes electrodes, voltage/current source, etc., is still a solid-state system.

[2]The term was coined by S. A. Wolf in 1996, as a name for a DARPA initiative for novel magnetic materials and devices.